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(54) Title: A METHOD AND APPARATUS FOR THE OPTIMAL PREDISTORTION OF AN ELECTROMAGNETIC SIGNAL IN A DOWNHOLE COMMUNICATION SYSTEM
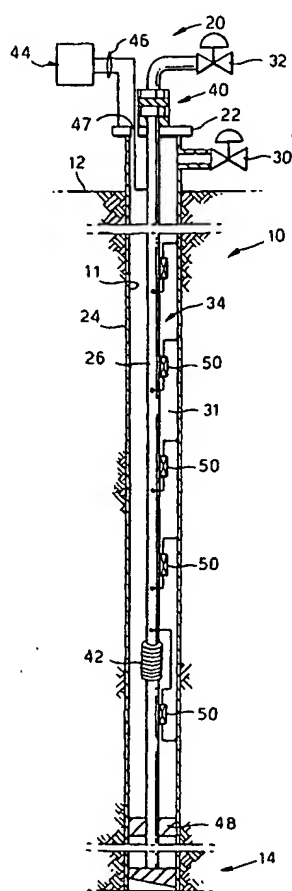
(57) Abstract: A method and apparatus for communicating a desired target signal along a piping structure is provided. Because of the lossy communication path presented by the piping structure, an input signal, which is transmitted from a first location on the piping structure, is consciously predistorted prior to transmission. The amount and nature of the predistortion applied to the input signal is determined by mathematically modeling the communication path between the first location and a second location. Predistortion of the input signal results in reception of an output signal at the second location that closely approximates the desired target signal. Application of this predistortion method of communicating is described in the context of communicating in the borehole of a petroleum well.

WO 01/59258 A1

A METHOD AND APPARATUS FOR THE OPTIMAL
PREDISTORTION OF AN ELECTROMAGNETIC SIGNAL
IN A DOWNHOLE COMMUNICATION SYSTEM

BACKGROUND OF THE INVENTION

Communication between two locations in an oil or gas well has been achieved using cables and optical fibres to transmit signals between the locations. In a petroleum

5   well, it is, of course, highly undesirable and in practice difficult to use a cable along the tubing string either integral to the tubing string or spaced in the annulus between the tubing string and the casing. The use of a cable presents difficulties for well operators

10   while assembling and inserting the tubing string into a borehole. Additionally, the cable is subjected to corrosion and heavy wear due to movement of the tubing string within the borehole. An example of a downhole communication system using a cable is shown in

15   PCT/EP97/01621.

U.S. Patent No. 4,839,644 describes a method and system for wireless two-way communications in a cased borehole having a tubing string. However, this system describes a communication scheme for coupling

20   electromagnetic energy in a TEM mode using the annulus between the casing and the tubing. This inductive coupling requires a substantially nonconductive fluid such as crude oil in the annulus between the casing and the tubing. Therefore, the invention described in U.S.

25   Patent No. 4,839,644 has not been widely adopted as a practical scheme for downhole two-way communication.

Another system for downhole communication using mud pulse telemetry is described in U.S. Patent

Nos. 4,648,471 and 5,887,657. Although mud pulse
telemetry can be successful at low data rates, it is of
limited usefulness where high data rates are required or
where it is undesirable to have complex, mud pulse
5   telemetry equipment downhole. Other methods of
communicating within a borehole are described in U.S.
Patent Nos. 4,468,665; 4,578,675; 4,739,325; 5,130,706;
5,467,083; 5,493,288; 5,576,703; 5,574,374; and
5,883,516.

10   PCT application, WO 93/26115 generally describes a
communication system for a sub-sea pipeline installation.
Importantly, each sub-sea facility, such as a wellhead,
must have its own source of independent power. In the
preferred embodiment, the power source is a battery pack
15   for startup operations and a thermoelectric power
generator for continued operations. For communications,
'115 applies an electromagnetic VLF or ELF signal to the
pipe comprising a voltage level oscillating about a DC
voltage level. Figs. 18 and 19 and the accompanying text
20   on pp. 40-42 does describe a crude system and method for
getting downhole pressure and temperature measurements.
However, the pressure and temperature sensors are passive
(Bourdon and bi-metallic strip) where movement varies a
circuit to provide resonant frequencies related to
25   temperature and pressure. A frequency sweep at the
wellhead looks for resonant spikes indicative of pressure
and temperature. The data at the well head is
transmitted to the surface by cable or the '115 pipeline
communication system.

30   The use of predistorted signals for communicating
along a non-linear transmission path is well documented.
U.S. Patent No. 5,959,499 generally describes a method
for determining a complex error signal and (during the
operation mode of the system) generating a predistorted

drive signal for a non-linear transmission path. U.S.
Patent No. 5,963,090, generally describes a circuit
applying non-linear characteristics to a signal. U.S.
Patent No. 5,251,328, generally describes compensating
for amplitude distortion in the communications channel by
predistorting the amplitude of transmitted signals. U.S.
Patent No. 4,291,277 generally describes compensating for
distortion introduced into a multiamplitude signal format
by predistorting the input signals before they are
subjected to non-linearities. The degree of
predistortion may vary and is updated to reflect changes
in the system. U.S. Patent No. 3,980,826 generally
describes a method and means for transmitting a waveform
of mixed frequency content over a transmission line to
reduce the effects of transmitting digital signals over
large distances.

Many of the wireless technologies attracting interest
in the oil and gas industry have been derived from the
commercial or defense industries. Since an oil well is
embedded in a conducting formation and completion fluids
are commonly filled with brine, it becomes difficult if
not impossible to employ off-the-shelf, turnkey wireless
systems in the subsurface environment. Whereas
traditional cellular or line-of-sight terrestrial
wireless systems enjoy the benefit of transmitting
electromagnetic waves in a lossless medium (e.g. the
air), subsurface wireless systems must necessarily
transmit in a conductive and hence, lossy medium.

One characteristic of this lossy transmission medium
is that electromagnetic signals are attenuated at a rate
proportional to the square root of the transmitted
frequency. This frequency-dependent attenuation is
called the "skin effect" resistance or impedance of the
transmission line. This skin effect attenuation causes

the edges of square wave pulses or general pulses with
fast rise times to be smoothed or "smeared". As a result,
it becomes increasingly difficult for the receiver
detector to resolve and extract the information content

5   of the original signal. Traditionally, to overcome this
difficulty, either power must be increased or the data
rate must be decreased so as to minimize the bit error
rate and maximize the distance between transmitter-
receiver pairs.

10   It would, therefore, be a significant advance in the
operation of petroleum wells if an alternate means for
compensating for the skin effect resistance of a lossy
transmission line were provided. In cases where
additional power is not available or the data rate cannot

15   be reduced, an alternate means of compensating for the
skin effect resistance is necessary to accurately
maintain the integrity of signals transmitted along the
line.

        All references cited herein are incorporated by

20   reference to the maximum extent allowable by law. To the
extent a reference may not be fully incorporated herein,
it is incorporated by reference for background purposes
and indicative of the knowledge of one of ordinary skill
in the art.

25   SUMMARY OF THE INVENTION.

        The problems created by the skin effect resistance of
a lossy transmission line are solved by predistorting an
input signal that will be transmitted along the line. By
modeling the transmission line between a first location

30   and a second location, an optimal predistortion can be
applied to the input signal before the signal is
transmitted from the first location on the transmission
line. The predistortion allows an output signal received

at the second location on the transmission line to be substantially similar to a desired target signal.

A communication system according to the present invention includes a pipe member with a first modem electrically connected to the pipe member at a first location. A second modem is electrically connected to the pipe member at a second location. A processor is provided for predistorting an input signal transmitted by the first modem to the pipe member. The second modem receives an output signal after the input signal is transmitted by the first modem.

A measurement system is provided for measuring an electrical formation characteristic for a petroleum well having a borehole and a piping structure that is located within the borehole. The measurement system includes a first modem electrically connected to the piping structure at a first location and a second modem electrically connected to the piping structure at a second location. The first modem imparts an input signal to the piping structure that is received as an output signal by the second modem. By observing the signal predistortion differences in the input signal and the output signal, the electrical formation characteristic of the well can be derived.

A method of communicating along a piping structure is also provided. The method is accomplished by predistorting an input signal and inputting the input signal onto the piping structure. The input signal is transmitted from a first location on the piping structure. An output signal is then received at a second location on the piping structure, the output signal being substantially similar to a desired target signal.

BRIEF DESCRIPTION OF THE DRAWINGS

    FIG. 1 is a schematic front view of a petroleum well according to the present invention, the petroleum well having a tubing string and a casing positioned within a borehole.

    FIG. 2 is an electrical schematic of a communications system according to the present invention, the communications system being positioned within the borehole of the petroleum well of FIG. 1.

    FIG. 3A is an equivalent circuit diagram of a communications path on which the communications system of FIG. 2 transmits and receives signals.

    FIG. 3B is a schematic of an input signal being transmitted from a first location on a piping structure and being received as an output signal at a second location on the piping structure.

    FIG. 4 is a flowchart illustrating a method of predistorting a signal according to the present invention, the signal being predistorted prior to transmission along the communications path of FIG. 3.

    FIG. 5 is a vertical section schematic of an oil well having a measuring system according to the present invention, the well being completed in a multi-layer formation.

    FIG. 6 is a schematic of a pair of waveforms illustrating signal predistortion differences due to changing reservoir conditions.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

    As used in the present application, a "piping structure" can be one single pipe, a tubing string, a well casing, a pumping rod, a series of interconnected pipes, rods, rails, trusses, lattices, supports, a branch or lateral extension of a well, a network of interconnected pipes, or other structures known to one of

ordinary skill in the art. The preferred embodiment
makes use of the invention in the context of an oil well
where the piping structure comprises tubular, metallic,
electrically-conductive pipe or tubing strings, but the

5   invention is not so limited. For the present invention,
at least a portion of the piping structure needs to be
electrically conductive, such electrically conductive
portion may be the entire piping structure (e.g. steel
pipes, copper pipes) or a longitudinal extending

10   electrically conductive portion combined with a
longitudinally extending non-conductive portion. In
other words, an electrically conductive piping structure
is one that provides an electrical conducting path from
one location where a power source is electrically

15   connected to another location where a device and/or
electrical return is electrically connected. The piping
structure will typically be conventional round metal
tubing, but the cross-sectional geometry of the piping
structure, or any portion thereof, can·vary in shape

20   (e.g. round, rectangular, square, oval) and size (e.g.
length, diameter, wall thickness) along any portion of
the piping structure.

A "valve" is any device that functions to regulate
the flow of a fluid. Examples of valves include, but are

25   not limited to, bellows-type gas-lift valves and
controllable gas-lift valves, each of which may be used
to regulate the flow of lift gas into a tubing string of
a well. The internal workings of valves can vary
greatly, and in the present application, it is not

30   intended to limit the valves described to any particular
configuration, so long as the valve functions to regulate
flow. Some of the various types of flow regulating
mechanisms include, but are not limited to, ball valve
configurations, needle valve configurations, gate valve

configurations, and cage valve configurations. Valves
can be mounted downhole in a well in many different ways,
some of which include tubing conveyed mounting
configurations, side-pocket mandrel configurations, or
permanent mounting configurations such as mounting the
valve in an enlarged tubing pod.

The term "modem" is used generically herein to refer
to any communications device for transmitting and/or
receiving electrical communication signals via an
electrical conductor (e.g. metal). Hence, the term is
not limited to the acronym for a modulator (device that
converts a voice or data signal into a form that can be
transmitted)/demodulator (a device that recovers an
original signal after it has modulated a high frequency
carrier). Also, the term "modem" as used herein is not
limited to conventional computer modems that convert
digital signals to analog signals and vice versa (e.g. to
send digital data signals over the analog Public Switched
Telephone Network). For example, if a sensor outputs
measurements in an analog format, then such measurements
may only need to be modulated (e.g. spread spectrum
modulation) and transmitted—hence no analog-to-digital
conversion is needed. As another example, a relay/slave
modem or communication device may only need to identify,
filter, amplify, and/or retransmit a signal received.

The term "processor" is used in the present
application to denote any device that is capable of
performing arithmetic and/or logic operations. The
processor may optionally include a control unit, a memory
unit, and an arithmetic and logic unit.

The term "sensor" as used in the present application
refers to any device that detects, determines, monitors,
records, or otherwise senses the absolute value of or a
change in a physical quantity. Sensors as described in

the present application can be used to measure
temperature, pressure (both absolute and differential),
flow rate, seismic data, acoustic data, pH level,
salinity levels, valve positions, or almost any other

5   physical data.

Also, the term "wireless" as used in this
application means the absence of a conventional,
insulated wire conductor e.g. extending from a downhole
device to the surface. Using the tubing and/or casing as

10   a conductor is considered "wireless".

The term "electronics module" in the present
application refers to a control device. Electronics
modules can exist in many configurations and can be
mounted downhole in many different ways. In one mounting

15   configuration, the electronics module is actually located
within a valve and provides control for the operation of
a motor within the valve. Electronics modules can also
be mounted external to any particular valve. Some
electronics modules will be mounted within side pocket

20   mandrels or enlarged tubing pockets, while others may be
permanently attached to the tubing string. Electronics
modules often are electrically connected to sensors and
assist in relaying sensor information to the surface of
the well. It is conceivable that the sensors associated

25   with a particular electronics module may even be packaged
within the electronics module. Finally, the electronics
module is often closely associated with, and may actually
contain, a modem for receiving, sending, and relaying
communications from and to the surface of the well.

30   Signals that are received from the surface by the
electronics module are often used to effect changes
within downhole controllable devices, such as valves.
Signals sent or relayed to the surface by the electronics

module generally contain information about downhole
physical conditions supplied by the sensors.

1.   Downhole Communication System

Referring to FIG. 1 in the drawings, a petroleum well
according to the present invention is illustrated. The
petroleum well is a gas-lift well 10 having a borehole 11
extending from a surface 12 into a production zone 14
that is located downhole. A production platform 20 is
located at surface 12 and includes a hanger 22 for
supporting a casing 24 and a tubing string 26. Casing 24
is of the type conventionally employed in the oil and gas
industry. The casing 24 is typically installed in
sections and is cemented in borehole 11 during well
completion. Tubing string 26, also referred to as
production tubing, is generally conventional comprising a
plurality of elongated tubular pipe sections joined by
threaded couplings at each end of the pipe sections.
Production platform 20 also includes a gas input throttle
30 to permit the input of compressed gas into an annular
space 31 between casing 24 and tubing string 26.
Conversely, output valve 32 permits the expulsion of oil
and gas bubbles from an interior of tubing string 26
during oil production.

Gas-lift well 10 includes a communication system 34
for providing power and two-way communication downhole in
well 10. Communication system 34 includes a lower
ferromagnetic choke 42 that is installed on tubing
string 26 to act as a series impedance to electric
current flow. The size and material of ferromagnetic
chokes 42 can be altered to vary the series impedance
value. Hanger 22 includes an insulated portion 40 that
electrically insulates tubing string 26 from casing 24
and from the remainder of the tubing string located above
surface 12. The section of tubing string 26 between

insulated portion 40 and lower choke 42 may be viewed as a power and communications path (see also FIGS. 2 and 3A). Lower choke 42 is manufactured of high permeability magnetic material and is mounted concentric and external

5   to tubing string 26. Choke 42 is typically hardened with injected epoxy to withstand rough handling.

A computer and power source 44 having power and communication feeds 46 is disposed outside of borehole 11 at surface 12. Communication feeds 46 pass through a

10   pressure feed 47 located in hanger 22 and are electrically coupled to tubing string 26 below insulated portion 40 of hanger 22. Power and communications signals are supplied to tubing string 26 from computer and power source 44.

15   A plurality of downhole devices 50 is electrically coupled to tubing string 26 between insulated portion 40 and lower ferromagnetic choke 42. Some of the downhole devices 50 comprise controllable gas-lift valves. Other downhole devices 50 may comprise electronics modules,

20   sensors, spread spectrum communication devices (i.e. modems), or conventional valves. Although power and communication transmission take place on the electrically isolated portion of the tubing string, downhole devices 50 may be mechanically coupled above or below

25   lower choke 42.

Referring to FIG. 2 in the drawings, communication system 34 is illustrated in more detail. Communication system 34 includes all of the components required to communicate along tubing string 26 and casing 24. One of

30   these components, computer and power source 44, includes an AC power source 120 and a master modem 122 electrically connected between casing 24 and tubing string 26. Two electronics modules 56 are connected to the tubing string 26 and the casing 24 downhole. Fewer

or more electronics modules could be positioned downhole.
Although electronics modules 56 appear identical, the
modules 56 may contain or omit different components. A
likely difference in each module could include a varying
5   array of sensors for measuring downhole physical
characteristics. It should also be noted that the
electronics modules 56 may or may not be an integral part
of a controllable valve. Each electronics module
includes a power transformer 124 and a data
10   transformer 128.

A slave modem 130 is electrically coupled to data
transformer 128 and is electrically connected to tubing
string 26 and casing 24. Slave modem 130 communicates
information to master modem 122 such as sensor
15   information received from electronics module 56. Slave
modem 130 receives information transmitted by master
modem 122 such as instructions for controlling the valve
position of downhole controllable valves. Additionally,
each slave modem 130 is capable of communicating with
20   other slave modems in order to relay signals or
information.

The present invention is directed to delivering
signals along communication system 34 between a first
modem and a second modem. It is important to note that
25   the designation of "first modem" and "second modem" can
be given to any of the modems previously mentioned
(master modem 122 and slave modems 130). More
specifically, master modem 122 could be designated as the
first modem and one of the slave modems 130 could be
30   designated the second modem. An input signal is
typically supplied by master modem 122 (the first modem)
to tubing string 26. An output signal is received by
slave modem 130 (the second modem). An alternative
designation could be to designate one of the slave

modems 130 as the first modem and another slave modem 130 as the second modem. Depending on the communication range that the slave modems 130 are capable of providing under specific well conditions, the transmission of sensor and control data up and down the well may require the relaying of signals between slave modems 130 rather than being passed directly between the surface and the selected downhole devices 50 (see FIG. 1). Under these circumstances, communication would be taking place between the designated slave modems 130.

Preferably the slave modems 130 are placed so that each can communicate with the next two slave modems up the well and the next two slave modems down the well. This redundancy allows communications to remain operational even in the event of the failure of one of the slave modems 130.

Because of the lossy transmission involved in communicating signals along a piping structure (e.g. a tubing string or casing), the input signal that is imparted to the piping structure by the first modem is often altered during transmission, resulting in the output signal received by the second modem being different from the original input signal. In any particular case, a desired target signal is the signal that is intended to be received at the second modem. By properly altering the input signal prior to transmission, the output signal received at the second modem will be substantially similar to the desired target signal.

The alteration performed on the input signal should be considered a predistortion of the input signal. Each of the modems illustrated in FIG. 2 (i.e. master modem 122 and slave modems 130) contains a processor 134 for determining a predistortion solution for each input signal. The amount and method of predistortion applied

to the input signal is determined based on mathematical
modeling of the communications path on which the input
signal is transmitted. The mathematical treatment of
this lossy communications path is detailed below.

5   2. <u>Derivation of the Lossy Transmission Line Model</u>

Suppose that a single tubing string is suspended
inside a fluid-filled casing using insulated packers and
that the casing and tubing string are used as the two
conductors for a transmission line. While this
10   configuration is similar to that of a coaxial cable, it
is unique in that the dielectric material separating the
cylindrical transmission lines may conduct electricity.
Referring to FIG. 3A in the drawings, an equivalent
circuit diagram for this situation is illustrated and
15   relies upon the following electrical characteristics of
the transmission line:

R = total series resistance per unit length, shown at a
resistor 140,

L = total series inductance per unit length, shown at an
20   inductor 142,

G = shunt conductance per unit length, shown at a
resistor 144, and

C = shunt capacitance per unit length, shown at a
capacitor 146.

25   Let a time-varying voltage be applied to the left-
hand side of the circuit. Then Kirchoff's law gives us
the following relation between the voltage, v(x,t) and
the current, i(x,t).

$$v(x + dx, t) - v(x, t) = -R \cdot dx \cdot i(x, t) - L \cdot dx \cdot \frac{\partial i}{\partial t}(x, t),$$

30   $$i(x + dx, t) - i(x, t) = -G \cdot dx \cdot v(x, t) - C \cdot dx \cdot \frac{\partial v}{\partial t}(x, t).$$

Dividing by dx and taking partials with respect to x,
we find

$$\frac{\partial^2 v}{\partial x^2} = (LC)\frac{\partial^2 v}{\partial t^2} + (LG + RC)\frac{\partial v}{\partial t} + (RG)v(x, t) ,$$

$$\frac{\partial^2 i}{\partial x^2} = (LC)\frac{\partial^2 i}{\partial t^2} + (LG + RC)\frac{\partial v}{\partial t} + (RG)i(x, t) .$$

Passing to the frequency domain by substituting a time-harmonic signal such that $\frac{\partial v}{\partial t} = j\omega v(x, t)$, we find that

5

$$\frac{\partial^2 v}{\partial x^2} - (R + j\omega L)(G + j\omega C)v(x, t) = 0,$$

$$\frac{\partial^2 i}{\partial x^2} - (R + j\omega L)(G + j\omega C)i(x, t) = 0.$$

Thus, $V(x) = V_1 e^{-\gamma x} + V_2 e^{\gamma x}$ and $I(x) = I_1 e^{-\gamma x} + I_2 e^{\gamma x}$, where the attenuation constant is given by

$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$. The constant α is called

10   the "attenuation component" with β yielding the

frequency-depended wave velocity of $v_\omega = \frac{\omega}{\beta}$.

Furthermore, the ratio of the voltage and current phasors give the characteristic impedance of the transmission line as

15      $$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} .$$

At high frequencies where the skin effect is significant, we find the skin effect impedance becomes

$Z_{skin} = K\sqrt{j\omega}.$

Therefore, the attenuation constant may be expressed

20   as a function of the complex angular rate of the phasor, $p = i\omega$

$$\gamma(p) = \left[(K\sqrt{p} + pL)(G + pC)\right]^{1/2}.$$

Expanding this using the binomial expansion formula for fractional exponents, it yields

$$\gamma(p) = p\sqrt{LC} + \frac{K}{2}\sqrt{\frac{C}{L}}p^{1/2} + \frac{G}{2}\sqrt{\frac{L}{C}}p^0 + \frac{KG}{2\sqrt{LC}}p^{-1/2}$$

+ higher order terms, where the higher order terms are on

the order of $O\left(p^{-1/2}\right) = O\left(\frac{1}{\sqrt{f}}\right)$. The constant $T = \sqrt{LC}$

represents the signal velocity, as it propagates down the entire length of the transmission line.

To facilitate the foregoing analysis, assume the shunt conductance of the transmission line is negligible so that $G = 0$. This may represent a case in which the completion fluid is an oil or very low conducting emulsion. Following the analysis of Wigington and Nahman in their 1957 article, *see,* Wiggington, R.I., Nahman, N.S., "Transient Analysis of Coaxial Cables Considering Skin Effect," Proceedings of the IRE, Feb. 1957, pp. 166-174, the attenuation exponent $\gamma(p)$ takes the form

$$\gamma(p) = \sqrt{(K\sqrt{p} + Lp)pC} \approx pT + \left(\frac{K}{2R_0}\right)p^{1/2},$$

where $R_0 = \sqrt{\frac{L}{C}}$. Therefore, for a transmission line of length l, the ratio of the received voltage to the transmitted voltage is

$$\frac{V(l)}{V(0)} = e^{-l\left(pT+(K/(2R_0))\sqrt{p}\right)} = f(p).$$

This may be used to define the transfer function that characterizes the signal distortion caused by skin-effect resistance and other losses. The transfer function $g(t)$ may be derived by taking the inverse Laplace transform of the function $f(p)$,

$$L^{-1}(G(p)) = g(t).$$

In special case that the shunt loss G is negligible, this becomes

$$g(t) = \begin{cases} \alpha(t - T1)^{-3/2} e^{-\beta / (t-T1)}, & \text{for } t \geq T1 \\ 0, & \text{otherwise.} \end{cases}$$

Here, the constants α and β are given by $LK/(4R_0\sqrt{\pi})$

5   and $\left(\dfrac{LK}{4R_0}\right)^2$, respectively. When the shunt loss, G, is

non-zero, the expression for the attenuation exponent involves three additional terms (given above) and complicates the inverse Laplace transform. Although a closed-form expression is omitted from this paper, a

10   numerical approximation to the transfer function may be constructed using commonly available software applications (e.g. Matlab or Mathematica).

3.   Analytical Characterization of the Received Signal

Using the numerically or analytically derived system

15   transfer function $g(t)$, it is possible to characterize an output signal $F_{out}(t)$ as a convolution of $g(t)$ with the function representing an input signal, $F_{in}(t)$, applied to the transmission line (i.e., tubing and casing). That is,

20    $$F_{out}(t) = \int_0^\infty F_{in}(t - \tau)g(\tau)d\tau .$$

Given the step function, $h(t) = \begin{cases} 0, & \text{for } t < 0, \\ 1, & \text{for } t \geq 0, \end{cases}$ its

associated output function is

$$F_{out}(t) = \begin{cases} \text{cerf}\left(\sqrt{\beta/(t - T1)}\right), & \text{for } t - T1 \geq 0, \\ 0, & \text{otherwise.} \end{cases}$$

For the sake of simplifying notation, we introduce a

25   new variable, $x = t - T1$, which represents time delayed

by the time required for a signal to propagate down the transmission line. Next, given the linear ramp function with rise time a,

$$F_{in}^{ramp}(t) = \begin{cases} 0, & \text{for } t < 0, \\ t/a, & \text{for } 0 \le t \le a, \\ 1, & \text{for } t > a, \end{cases}$$

the function describing its associated output is given by

$$F_{out}^{ramp}(t) = F_{out}(x + T1) = \frac{1}{a} \int_{x-a}^{x} \text{cerf}\left(\sqrt{\frac{\beta}{\tau}}\right) d\tau, \text{ when } x \ge 0.1$$

Using this formula, it is possible to characterize the response of any pulse signal of duration t_P and with rise and fall time a. Namely, for

$$F_{in}^{pulse}(t) = \begin{cases} 0, & \text{for } t < 0, \\ t/a, & \text{for } 0 \le t \le a, \\ 1, & \text{for } a < t \le a + t_P, \\ -t/a + \left(2 + t_P/a\right), & \text{for } a + t_P < t \le 2a + t_P, \\ 0, & \text{for } t > 2a + t_P, \end{cases} =$$

$$= F_{in}^{ramp}(t) - F_{in}^{ramp}\left(t - (a + t_P)\right)$$

we have

$$F_{out}^{pulse}(t) = F_{out}^{pulse}(x + T1) = (F_{in}^{ramp}(t) - F_{in}^{ramp}(t - (a + t_p))) * g(t).$$

4. Application of Control Theory to Derive Optimal Waveform Predistortion

Referring to FIG. 3B in the drawings, an input signal is transmitted from a first location 148 on a piping structure 150 (e.g. tubing string or casing). The input signal is received as an output signal at a second location 151 on the piping structure 150. Suppose we need to best choose the input signal (i.e. waveform), $F_{in}(t)$, in such a way that the resulting output signal

(i.e. waveform), $F_{out}(t)$, most closely matches a desired target signal (i.e. waveform), $F_{target}(t)$.

Writing the functions representing the input, output and desired target signals as piecewise linear approximations
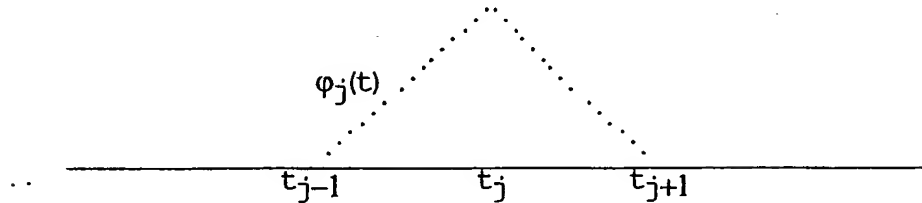
$$F_{in}(t) = c_0 \varphi_0(t) + c_1 \varphi_1(t) + \cdots + c_{N-1} \varphi_{N-1}(t),$$

$$F_{out}(t) = w_0 \tilde{\varphi}_0(t) + w_1 \tilde{\varphi}_1(t) + \cdots + w_{N-1} \tilde{\varphi}_{N-1}(t),$$

$$F_{target}(t) = t_0 \tilde{\varphi}_0(t) + t_1 \tilde{\varphi}_1(t) + \cdots + t_{N-1} \tilde{\varphi}_{N-1}(t),$$

where $\varphi_j(t)$ is the piecewise linear "hat" basis function at the transmitter (system control) of width $h = \Delta t$ and centered at node $t_j = jh$ and $\tilde{\varphi}_j(t) = \varphi_j(t - T1)$ is the basis function at the receiver location (system state delayed by time constant T).

Using the distortion transfer function, $g(t)$, we may write the output function as a weighted sum of convolutions with the piecewise linear basis functions,

$$F_{out}(t) = \sum_{j=0}^{N-1} c_j \left(\varphi_j(t) * g(t) \right).$$

To determine the input signal that must yield a "best approximation" to the desired target function, an optimal control problem is formulated. Towards this end, we wish to find the control vector $\bar{c} = \begin{pmatrix} c_0 & \cdots & c_{N-1} \end{pmatrix}^T$ that minimizes the quadratic functional

$$J(\bar{c}) = \eta_1 \left\| F_{out} - F_{target} \right\|^2 + \eta_2 \left\| \bar{c} \right\|^2$$

subject to the linear constraint that
$F_{out}(t) = F_{in}(t) * g(t)$ and where η_1 and η_2 are any desired
weighting coefficients (non-negative).

5   To solve this optimal control problem, the associated
output signal for each input basis function, $\varphi_j(t)$, is
calculated. These output signals are given by $\varphi_j(t) * g(t)$
and may each be approximated by a piecewise linear
interpolant, $\varphi_j(t) * g(t) = \sum_{i=0}^{N-1} s_i^j \tilde{\varphi}_i(t)$. The vector

$\bar{s}^j = \left(s_0^j \ \cdots \ s_{N-1}^j \right)^T$, formed by extracting the coefficients

10   of this linear approximation to $\varphi_j(t) * g(t)$, represents the
state vector response evoked by the application of a
single basis function of the control space.

       Define the matrix of evoked state responses for each
of the basis functions by $M = \left(s^0 \ s^1 \ \cdots \ s^{N-1} \right)$.

15   Then for each given input,
$F_{in}(t) = c_0 \varphi_0(t) + c_1 \varphi_1(t) + \cdots + c_{N-1} \varphi_{N-1}(t)$, the associated output,
$F_{out}(t) = w_0 \tilde{\varphi}_0(t) + w_1 \tilde{\varphi}_1(t) + \cdots + w_{N-1} \tilde{\varphi}_{N-1}(t)$, is given by $\bar{w} = M \bar{c}$.

       Rephrasing the control problem as to minimize the
quadratic "cost" functional $J(\bar{c}) = \eta_1 \left\| M\bar{c} - \bar{t} \right\|^2 + \eta_2 \left\| \bar{c} \right\|^2$,

20   where $F_{target}(t) = t_0 \tilde{\varphi}_0(t) + t_1 \tilde{\varphi}_1(t) + \cdots + t_{N-1} \tilde{\varphi}_{N-1}(t)$ is the
desired target signal and $\bar{s} = M\bar{c}$ is the linear
constraint. Note that in this case, the matrix M was
derived using the Laplace transform and convolutions of
the derived transfer function with a set of basis

25   functions. Alternatively, M could be represented as a
forward solution operator for the coupled wave equations
referenced herein. Now, the gradient of the cost

functional is given by $\nabla J(\bar{c}) = 2\eta_1 M^T(M\bar{c} - \bar{t}) + 2\eta_2\bar{c}$, and the optimal control is achieved when $\nabla J(\bar{c}) = 0$ or when $(\eta_1 M^T M + \eta_2 I)\bar{c} = M^T\bar{c}$.

The solution of this linear system yields the necessary predistortion required to produce a "best" approximation to the desired target signal at the receiver. In the case that M is a forward solution operator for the wave equation, M^T is the backwards-in-time solution operator for the wave equation with sign changes on the first derivative coefficients.

5. Implementation

The method and apparatus of the present invention broadly includes a means of compensating for the skin effect resistance of a transmission path by predistorting an emitted wave, or input signal, at a transmitting station on the transmission path so as to produce an output wave, or output signal at a receiver station that matches an actual desired target wave. In other words, the input signal is consciously distorted prior to transmission in such a way that the physics of the lossy transmission line constructively distorts the applied predistortion and results in a near-perfect replication of the input signal at the receiver station.

The predistortion amount, or predistortion solution, is obtained by developing a model for the skin effect resistance or attenuation caused by the transmission path. As previously described, this model is based on an equivalent circuit model for a tubing string suspended in a casing filled with completion fluid. After developing a model, a closed system control problem is formulated together with an iterative means of solving the control problem. The control problem has an optimal solution (i.e. a predistorted input signal) when the received

output signal is a "best match", or is substantially
similar to the desired target signal as measured by a
least squares method. This iterative process defines the
power-on negotiation process that must take place between
5   communication station pairs so as to optimally determine
the level of predistortion required to compensate for the
skin effect attenuation. Other methods of developing
such a model will be known to those of skill in the art,
such as Artificial Neural Net and other AI solutions.

10   Referring to FIG. 4 in the drawings, the steps
involved in optimally predistorting the input signal are
illustrated. It should be noted that the actual
selection and determination of the predistorted input
signal is based on the mathematical solution to the
15   control problem described previously. The first step,
"Determine Desired Target Signal" 152, is performed prior
to Predistort Input Signal 153. In a lossless
transmission, the desired target signal would be equal to
the input signal transmitted and the output signal
20   received. However, since the transmission is lossy, the
input signal is predistorted to achieve an output signal
that is substantially similar to the desired target
signal. Predistort Input Signal 153 includes the
following substeps: Select Waveform 154, Calculate
25   Waveform 155, Apply Waveform 156, Select Power Level 158,
Calculate Power Level 159, Apply Power Level 160, Select
Center Frequency 162, Calculate Center Frequency 163,
Apply Center Frequency 164, Select Chip Set 166,
Calculate Chip Set 167, Apply Chip Set 168, Select
30   Bandwidth 170, Calculate Bandwidth 171, and Apply
Bandwidth 172. Each of the "calculate" and "apply" steps
is contingent on the successful determination of the
related "select" step. For example, if a spread spectrum
communication system is being used to transmit signals, a

center frequency does not need to be selected. Instead,
Select Chip Set 166 is answered affirmatively such that a
chip set is calculated and applied by Calculate Chip
Set 167 and Apply Chip Set 168. Alternatively, if an

5   FSK- or PSK-modulated communication system is used, a
chip set is not selected. Instead, Select Center
Frequency 162 is answered affirmatively such that a
center frequency is calculated and applied by Calculate
Center Frequency 163 and Apply Center Frequency 164.

10   After completing Predistort Input Signal 153, the
predistorted input signal is transmitted in accordance
with Transmit Input Signal From First Location 174. This
step is presumably performed by the first, or
transmitting modem. The second, or receiving modem

15   receives the output signal in accordance with Receive
Output Signal at Second Location 176.

It is envisioned that the aforementioned optimal
control solver will be implemented in a two-way modem in
software and/or hardware form. When a communications

20   session is to be established between two locations, the
system first enters into a "tune-up" or calibration phase
in which the optimal predistortion is determined at each
location so as to maximize the data throughput and/or
minimize the bit error rate. During this "tune-up"

25   phase, frequency pairs required to perform FSK (frequency
shift keying) modulation or bandwidth/chipset
configurations required to transmit data using a suitable
spread-spectrum algorithm (such as CDMA) are optimally
chosen. Furthermore, if the communication architecture

30   consists of multiple modem stations, multiple
predistortion parameters may be derived for each source-
receiver pair so that the entire communication
infrastructure may operate at maximum efficiency.

Referring to FIG. 5 in the drawings, a measurement
system 182 for characterizing the hydrocarbon saturation
of a formation is illustrated. Currently, it is
envisioned that the casing and production tubing are used
5   as the two conductors for a transmission line, analogous
to a coaxial cable. If, on the other hand, the entire
production tubing and casing are to be considered as a
single conductor 184, a ground-return could be used to
complete the electrical connection. In this case, the
10   level of applied predistortion required for a source-
receiver pair would yield the homogenized electrical
properties for the formation between a source, or first
modem 186 and a receiver, or second modem 188. These
properties could include the per-unit-length conductance
15   and capacitance and, thus, may be used to characterize
the amount of hydrocarbon saturation in the formation
outside of the well casing.

Modems 188 are each positioned at a different station
along the path of the well that penetrates several
20   formation layers. A station 190 is positioned within
Formation A, a station 192 is positioned within
Formation B, and a station 194 is positioned within
Formation C. Each of the formation layers has measurable
per-unit-length resistivity and dielectric properties
25   that depend on the constituent rock composition,
geological structure, fluid content (oil, water, gas),
invaded fluid content and formation damage due to the
presence of the well.

Upon initiating communication sessions with its
30   nearest neighbors, transmission station 194 determines
the optimum predistortion required to achieve a given
data rate while minimizing the bit error rate. Using
numerical analytical tools, such as finite element or
finite difference analysis, phenomenological modeling of

electromagnetic wave propagation in the subsurface may be
conducted. These tools may be directed towards solving
the "inverse problem" of deriving electrical formation
characteristics - resistivity and dielectric permittivity
5   - given signal predistortion differences in the input and
the output signals.

An example of reservoir monitoring using this
invention is the tracking and positioning of oil-water
contacts over the production lifetime of a field. At the
10   beginning of a field's production life, sufficient oil is
present in the reservoir to justify production. The
initial oil-water contact at this point in time is OWC1.
Since the electrical losses in the oil zone are
surpressed by the presence of the fluidic insulator
15   (oil), transceiver stations along a well inside the oil
zone are able to transmit signals with minimal
attenuation. Referring to FIG. 6 in the drawings, an
example of the initial applied predistortion to a
transmitted signal 196 is illustrated. However, after
20   years of production, the produced oil and gas are
replaced by water from the surrounding formation,
resulting in a rise in the oil-water contact to OWC2.
Reservoir fluid surrounding the transceiver stations no
longer insulate the system from electrical losses. As a
25   result, additional predistortion must be applied to a
transmitted signal in order to overcome distortion caused
by skin-effect resistance and frequency-dependent
attenuation. A new predistorted waveform 198 is also
depicted in FIG. 6. By analyzing the signal
30   predistortion differences in signals 196 and 198, it is
possible to derive, for instance, the new location of the
oil water contact, OWC2.

Even though many of the examples discussed herein are
applications of the present invention in petroleum wells,

the present invention also can be applied to other types
of wells, including but not limited to water wells and
natural gas wells.

One skilled in the art will see that the present
invention can be applied in many areas where there is a
need to provide a communication system within a borehole,
well, or any other area that is difficult to access.
Also, one skilled in the art will see that the present
invention can be applied in many areas where there is an
already existing conductive piping structure and a need
to route power and communications to a location on the
piping structure. A water sprinkler system or network in
a building for extinguishing fires is an example of a
piping structure that may be already existing and may
have a same or similar path as that desired for routing
power and communications. In such case another piping
structure or another portion of the same piping structure
may be used as the electrical return. The steel
structure of a building may also be used as a piping
structure and/or electrical return for transmitting power
and communications in accordance with the present
invention. The steel rebar in a concrete dam or a street
may be used as a piping structure and/or electrical
return for transmitting power and communications in
accordance with the present invention. The transmission
lines and network of piping between wells or across large
stretches of land may be used as a piping structure
and/or electrical return for transmitting power and
communications in accordance with the present invention.
Surface refinery production pipe networks may be used as
a piping structure and/or electrical return for
transmitting power and communications in accordance with
the present invention. Thus, there are numerous

applications of the present invention in many different areas or fields of use.

It should be apparent from the foregoing that an invention having significant advantages has been provided. While the invention is shown in only a few of its forms, it is not just limited but is susceptible to various changes and modifications without departing from the spirit thereof.

Appendix A contains source code and optimal predistortion solutions required to transmit 100, 500 and 2000 Mbit/second down a 100 meter piece of standard Black Box Plenum Ethernet coaxial cable. Graphs whose titles begin with "Control" describe the time-varying predistorted pulse function to be transmitted at the source end of the transmission line. Graphs whose titles begin with "Target and Output" describe the desired target signal (solid line) and the received output signal (dashed line). As can be seen from the graphs, the received output signals match well the desired target signal.

C L A I M S

1. A communication system comprising:

a pipe member;

a first modem electrically connected to the pipe
member at a first location for transmitting an input

5   signal along the pipe member;

a second modem electrically connected to the pipe
member at a second location for receiving an output
signal along the pipe member after the first modem
transmits the input signal; and

10   a processor coupled to the first modem for
predistorting the input signal prior to the input signal
being transmitted by the first modem to the second modem
along the pipe member.

2. The communications system according to claim 1
15   wherein the predistortion of the input signal prior to
transmission is such that the output signal received by
the second modem is substantially similar to a target
signal.

3. The communications system according to claim 1
20   wherein the processor is an integral portion of the first
modem.

4. The communications system according to claim 1
further comprising:

a second processor for predistorting a second input
25   signal transmitted by the second modem along the pipe
member; and

wherein the first modem receives a second output
signal after the second modem transmits the second input
signal.

5.   The communications system according to claim 4
wherein the predistortion of the second input signal
prior to transmission is such that the second output
signal received by the first modem is substantially
similar to a second target signal.

6.   The communications system according to claim 1
wherein the pipe member is an interconnected plurality of
pipes in a borehole of a petroleum well.

7.   In a petroleum well having a piping structure and a
wireless communication system for communicating signals
along the piping structure, a method for delivering an
input signal from a first location to a second location,
the method comprising the steps of:

    determining an optimum predistortion amount for the
input signal to achieve a desired reception of a target
signal at the second location;

    applying the predistortion amount to the input
signal; and

    transmitting the predistorted input signal along the
piping structure from the first location to the second
location.

8.   The method according to claim 7, wherein the
communication system includes a first modem electrically
connected to the piping structure at the first location
and a second modem electrically connected to the piping
structure at the second location.

9.   The method of claim 7, wherein the desired target
signal approximates a desired data transmission rate
while minimizing bit rate error.

10. The method according to claim 7, further comprising
the steps of:

    providing an electrically insolated portion along the
piping structure;

providing an induction choke disposed concentrically
around the piping structure; and

wherein the transmitting step further comprises
transmitting the input signal along the piping structure
5   between the electrically insolated portion and the
ferromagnetic choke.

11. The method according to claim 7, further comprising
the steps of:

providing an upper induction choke and a lower
10   induction choke disposed concentrically around the piping
structure; and

wherein the transmitting step further comprises
transmitting the input signal along the piping structure
between the upper induction choke and the lower induction
15   choke.

12. In a petroleum well having a borehole and a piping
structure disposed within the borehole, the improvement
comprising a wireless communications system that
predistorts an input signal prior to sending the input
20   signal along the piping structure from a first location
to a second location.

13. A petroleum well having a borehole and a piping
structure disposed within the borehole comprising:

a first modem electrically connected to the piping
25   structure at a first location, the first modem configured
to impart an input signal to the piping structure;

a second modem electrically connected to the piping
structure at a second location, the second modem
configured to receive an output signal after the input
30   signal is sent by the first modem;

a processor for predistorting the input signal prior
to the input signal being transmitted by the first modem
along the piping structure; and

wherein the input signal is predistorted such that the output signal received by the second modem closely matches a target signal.

14. The petroleum well according to claim 13, wherein the processor is an integral part of the first modem.

15. The petroleum well according to claim 13 further comprising:

an electrically insulated portion located on the piping structure;

a ferromagnetic choke disposed concentrically around the piping structure; and

wherein the signals transmitted and received by the first and second modems are communicated along the piping structure between the electrically insulated portion and the ferromagnetic choke.

16. The petroleum well according to claim 13 further comprising:

an upper ferromagnetic choke and a lower ferromagnetic choke disposed concentrically around the piping structure; and

wherein the signals transmitted and received by the first and second modems are communicated along the piping structure between the upper and lower ferromagnetic chokes.

17. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a transmitted waveform to the input signal.

18. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a power level to the input signal.

19. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a center frequency to the input signal.

20. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a bandwidth to the input signal.

21. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a chip set to the input signal.

22. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a transmitted waveform, a power level, a center frequency, and a bandwidth to the input signal.

23. The petroleum well according to claim 13 wherein the processor predistorts the input signal by calculating and applying a transmitted waveform, a power level, a chip set, and a bandwidth to the input signal.

24. The petroleum well according to claim 13 wherein the piping structure is production tubing located within the borehole of the well.

25. The petroleum well according to claim 13 wherein the piping structure is a casing cemented within the borehole of the well.

26. The petroleum well according to claim 13 wherein:

the transmission of the input signal along the piping structure is a lossy transmission that causes bit error in the input signal; and

the predistortion of the input signal prior to transmission by the first modem decreases the bit error rate along the piping structure, thereby causing the output signal received by the second modem to approximate the desired target signal.

27. The petroleum well according to claim 13 wherein the processor calculates the proper predistortion for the input signal using finite element analysis to model electromagnetic wave propagation along the piping structure.

28. A measurement system for measuring an electrical formation characteristic in a petroleum well having a borehole and a piping structure disposed within the borehole, the measurement system comprising:

    a first modem electrically connected to the piping structure at a first location, the first modem configured to impart an input signal to the piping structure;

    a second modem electrically connected to the piping structure at a second location, the second modem configured to receive an output signal after the input signal is sent by the first modem; and

    wherein the electrical formation characteristic of the well is derived by observing a signal predistortion difference in the input signal and the output signal.

29. The measurement system according to claim 28, wherein the electrical formation characteristic includes resistivity to electromagnetic wave propagation.

30. The measurement system according to claim 28, wherein the electrical formation characteristic includes dielectric permittivity.

31. The measurement system according to claim 28, wherein the electrical formation characteristics of the petroleum well depend on constituent rock composition, geological structure, fluid content, invaded fluid content, and formation damage caused by the presence of the well.

32. The measurement system according to claim 28, wherein the measurement system is used for tracking oil-water contacts in an oil field.

33. A method for communicating along a piping structure comprising the steps of:

    predistorting an input signal;

    inputting the predistorted input signal at a first location on the piping structure for transmission along the piping structure; and

receiving an output signal at a second location on the piping structure, the output signal being substantially similar to a desired target signal that was pre-selected prior to predistortion of the input signal.

5   34. The method according to claim 33 further comprising the steps of:

providing a first modem electrically connected to the piping structure at the first location and a second modem electrically connected to the piping structure at the

10 second location; and

wherein the inputting step is accomplished by the first modem and the receiving step is accomplished by the second modem.

35. The method according to claim 33, wherein the step of

15 predistorting an input signal further comprises the step of calculating and applying a transmitted waveform to the input signal.

36. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step

20 of calculating and applying a power level to the input signal.

37. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step of calculating and applying a center frequency to the

25 input signal.

38. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step of calculating and applying a bandwidth to the input signal.

30 39. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step of calculating and applying a chip set to the input signal.

40. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step of calculating and applying a transmitted waveform, a power level, a center frequency, and a bandwidth to the

5   input signal.

41. The method according to claim 33, wherein the step of predistorting an input signal further comprises the step of calculating and applying a transmitted waveform, a power level, a chip set, and a bandwidth to the input

10   signal.

42. The method according to claim 33 further comprising:

        providing a first modem electrically connected to the piping structure at the first location and a second modem electrically connected to the piping structure at the

15   second location, wherein the inputting step is accomplished by the first modem and the receiving step is accomplished by the second modem; and

        calibrating the first modem to optimally predistort the input signal prior to transmission of the input

20   signal along the piping structure such that the output signal received at the second modem is substantially similar to the desired target signal.

43. The method according to claim 42, wherein the step of calibrating the first modem further comprises the step of

25   choosing frequency pairs for performing frequency shift keying modulation.

44. The method according to claim 42, wherein the step of calibrating the first modem further comprises the step of choosing bandwidth/chipset configurations for

30   transmitting signals using a spread spectrum algorithm.

45. The method according to claim 33 further comprising the steps of:

        providing an electrically insulated portion along the piping structure;

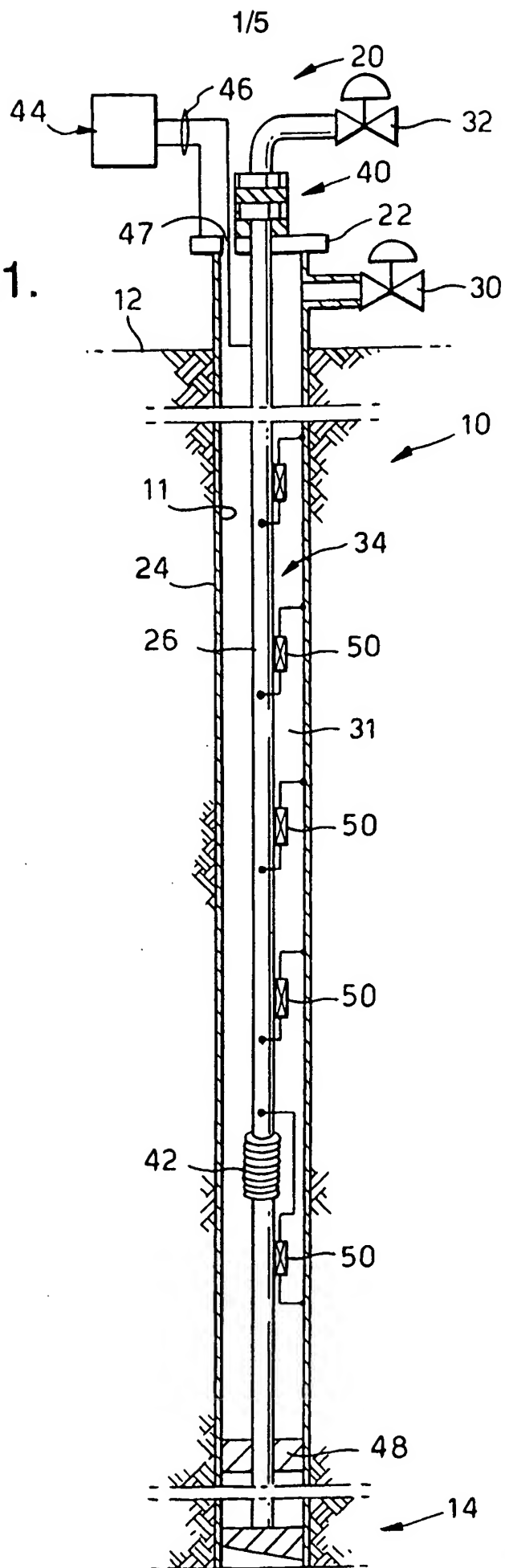providing a ferromagnetic choke disposed concentrically around the piping structure; and

wherein the inputting and the receiving steps occur on a section of the piping structure located between the

5   electrically insulated portion and the ferromagnetic choke.

46. The method according to claim 33 further comprising the steps of:

providing an upper ferromagnetic choke and a lower

10   ferromagnetic choke disposed concentrically around the piping structure; and
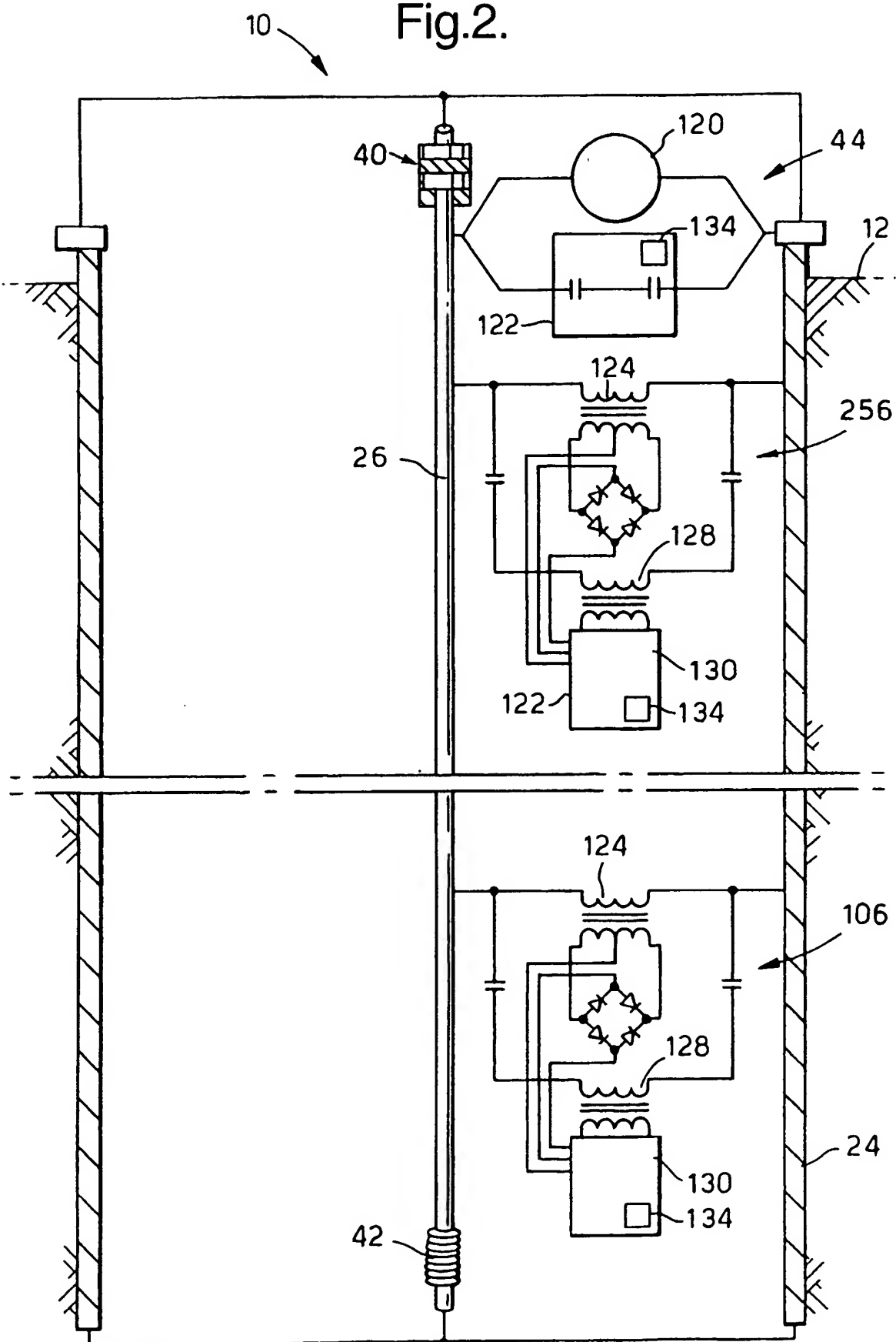
wherein the inputting and the receiving steps occur on a section of the piping structure located between the upper ferromagnetic choke and the lower ferromagnetic
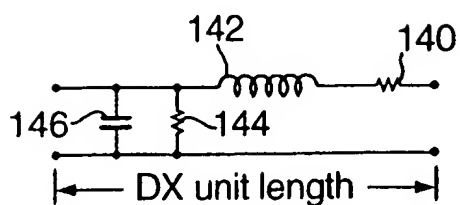
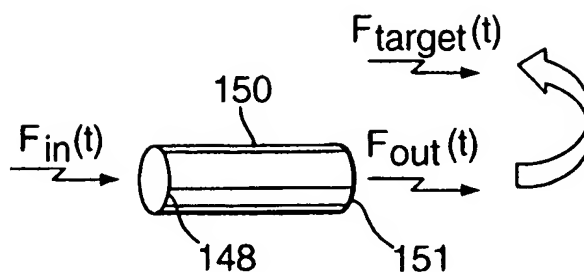15   choke.

Fig.1.

Fig.2.
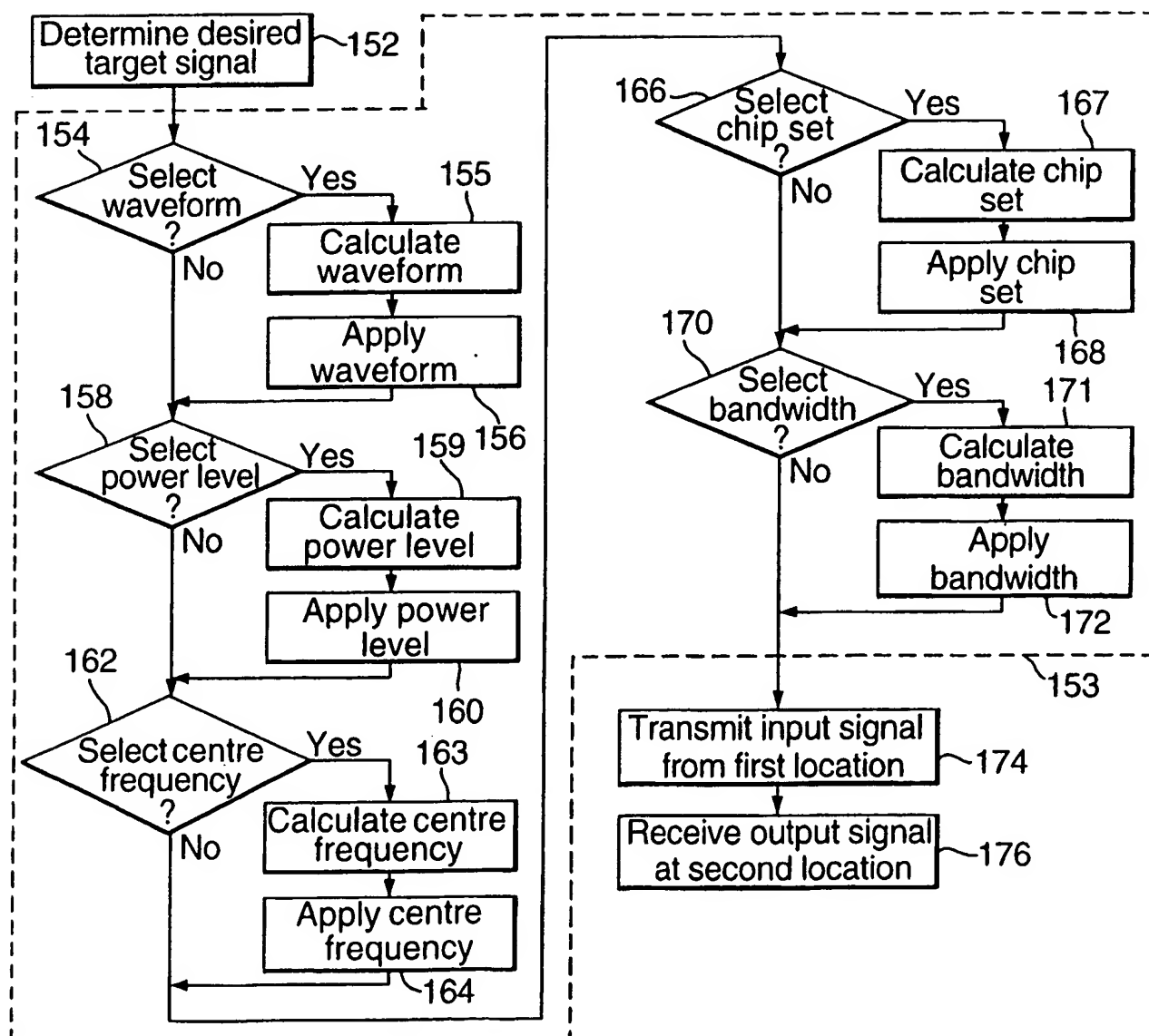
Fig.3A.

Fig.3B.

Fig.4A.

Fig.4B.

Determine desired target signal ~152

162 Select centre frequency ? — Yes — 163 — Calculate centre frequency

No

Apply centre frequency ~164

154 Select waveform ? — Yes — 155 — Calculate waveform

No

Apply waveform

156

166 Select chip set ? — Yes — 167 — Calculate centre frequency

No

Apply centre frequency

158 Select level power ? — Yes — 159 — Calculate power level

No

Apply power level

160

168

170 Select bandwidth ? — Yes — 171 — Calculate bandwidth

No

Apply bandwidth ~172

153

Transmit input signal from first location ~174

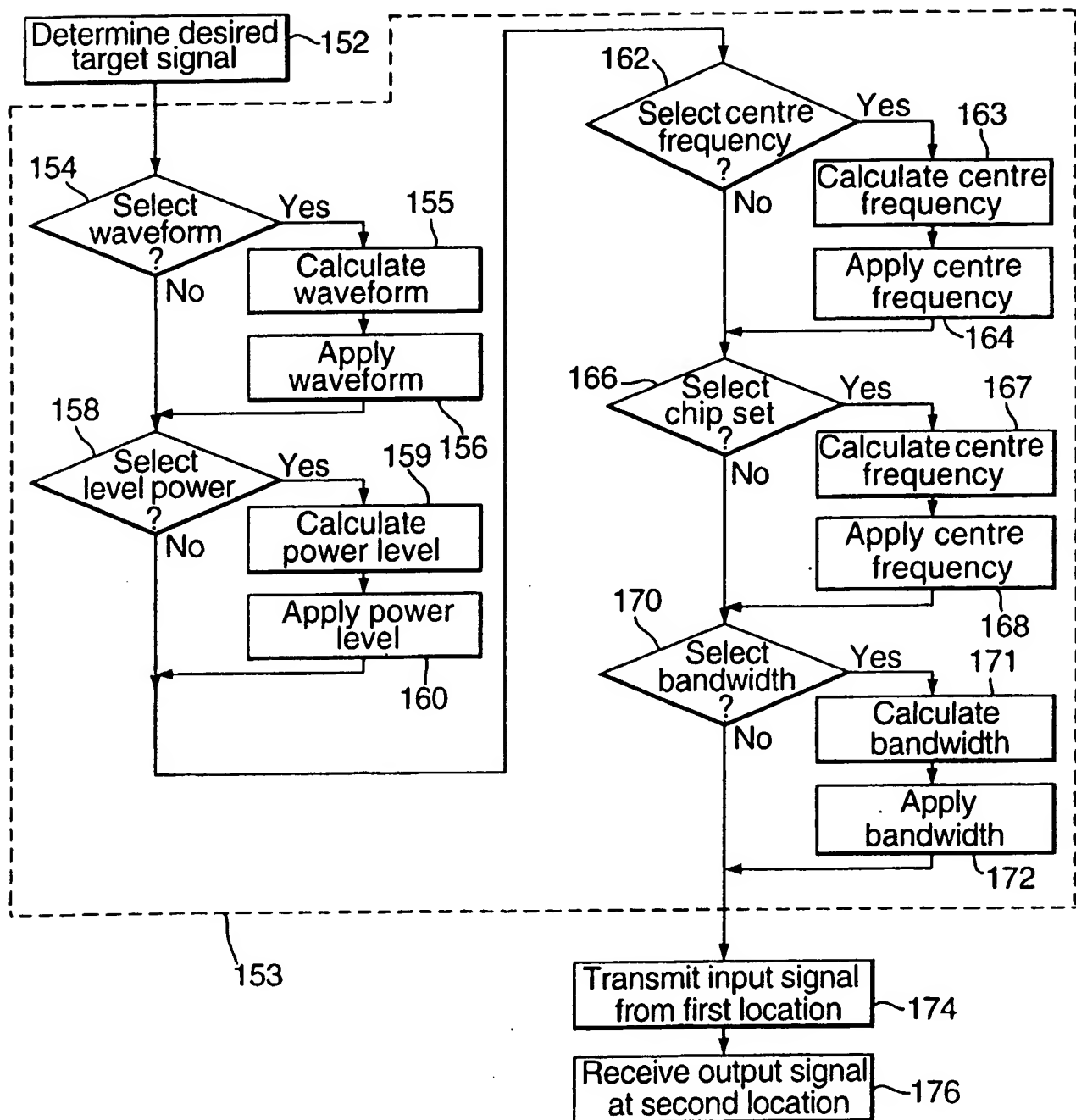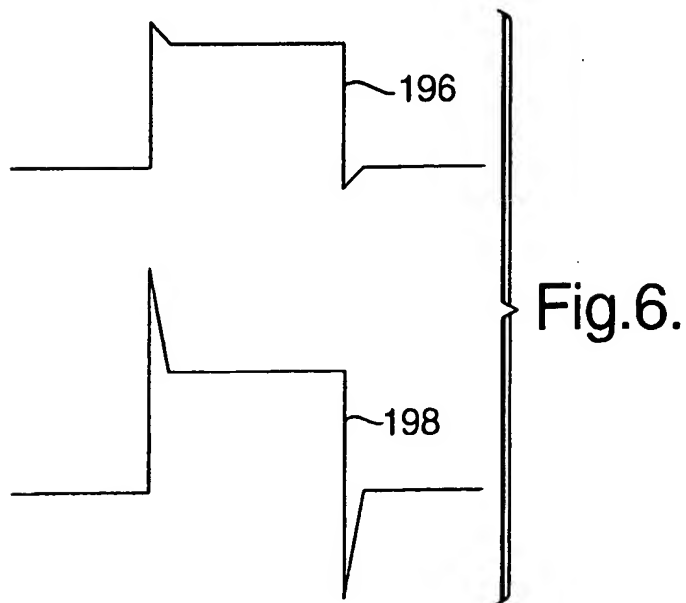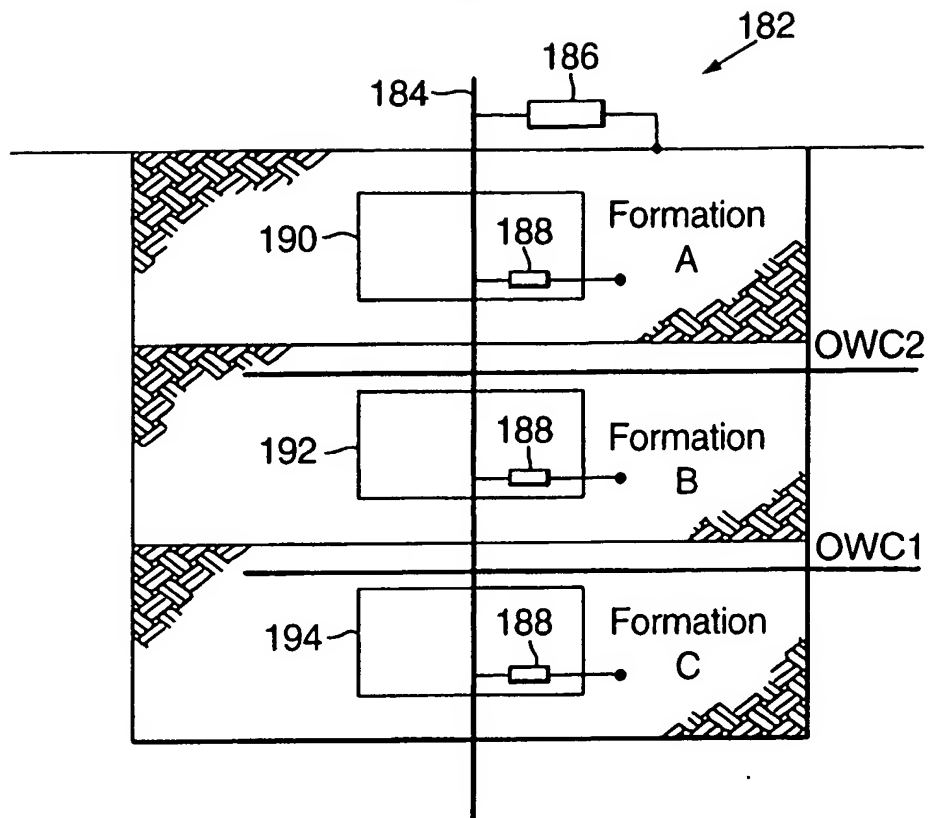Receive output signal at second location ~176

Fig.5.

Fig.6.

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   E21B47/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 160 925 A (RORDEN LOUIS H ET AL) 3 November 1992 (1992-11-03) column 23, line 5 -column 23, line 30; figure 13 ---	1-46
Y	EP 0 295 178 A (SCHLUMBERGER LTD ;SCHLUMBERGER PROSPECTION (FR)) 14 December 1988 (1988-12-14) page 9, line 20 -page 8, line 35; figures 4,10-13 abstract ---	1-46
Y	US 4 648 471 A (BORDON ERNESTO E) 10 March 1987 (1987-03-10) cited in the application column 4, line 34 -column 4, line 60; figures 1,2 ---	1-46

-/--

[X]	Further documents are listed in the continuation of box C.	[X]	Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 May 2001	31/05/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Tompouloglou, C

Form PCT/ISA/210 (second sheet) (July 1992)

1

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
	C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT	
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